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OUTSHINING THE QUASARS AT REIONIZATION: THE X-RAY SPECTRUM AND LIGHT CURVE OF THE REDSHIFT 6.29 GAMMA-RAY BURST GRB 050904

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ABSTRACT

Gamma-ray burst (GRB) 050904 is the most distant X-ray source known, at $z = 6.295$, comparable to the farthest AGNs and galaxies. Its X-ray flux decays, but not as a power law; it is dominated by large variability from a few minutes to at least half a day. The spectra soften from a power law with photon index $\Gamma = 1.2$–1.9 and are well fit by an absorbed power law with possible evidence of large intrinsic absorption. There is no evidence for discrete features, in spite of the high signal-to-noise ratio. In the days after the burst, GRB 050904 was by far the brightest known X-ray source at $z > 4$. In the first minutes after the burst, the flux was $>10^{-9}$ ergs cm^{-2} s^{-1} in the 0.2–10 keV band, corresponding to an apparent luminosity $>10^5$ times larger than the brightest AGNs at these distances. More photons were acquired in a few minutes with *Swift* XRT than *XMM-Newton* and *Chandra* obtained in ∼300 ks of pointed observations of $z > 5$ AGNs. This observation is a clear demonstration of concept for efficient X-ray studies of the high-*z* IGM with large-area, high-resolution X-ray detectors and shows that early-phase GRBs are the only backlighting bright enough for X-ray absorption studies of the IGM at high redshift.

Subject headings: gamma rays: bursts — intergalactic medium — quasars: absorption lines — X-rays: galaxies — X-rays: general

1. INTRODUCTION

The promise of γ-ray bursts (GRBs) as cosmic lighthouses to rival quasars is being fulfilled in the areas of GRB damped Lyα absorbers (Vreeswijk et al. 2004; Watson et al. 2005; Starling et al. 2005; Chen et al. 2005), as tracers of star formation (Jakobsson et al. 2005; Fynbo et al. 2003; Bloom et al. 2002), and as early warnings of supernovae (e.g., SN 2003lw; see Thomsen et al. 2004; Cobb et al. 2004; Malesani et al. 2004). Central to this promise is the belief that GRBs from early in the universe can be detected ($z \sim 10$; e.g., Mészáros & Rees 2003). But while the highest redshifts of active galactic nuclei (AGNs) and galaxies increased, for 5 years the highest GRB redshift was $z = 4.50$ (Andersen et al. 2000). Now a GRB at $z > 6$ has finally been detected: GRB 050904 at $z = 6.295 \pm 0.002$ (Kawai et al. 2005; see also Haislip et al. 2005; Tagliaferri et al. 2005; Price et al. 2005). To date, X-ray observations of $z > 5$ AGNs with *Chandra* and *XMM-Newton* have obtained bare detections (Schwartz 2002; Brandt et al. 2002; Mathur et al. 2002; Vignali et al. 2003; Bechtold et al. 2003), and from the most luminous, spectra with a few hundred counts using long exposures (Farrah et al. 2004; Grupe et al. 2006; Shemmer et al. 2005), allowing constraints to be placed on AGN evolution up to the edge of reionization. In this Letter we examine the X-ray spectra and light curve of GRB 050904 from the *Swift* X-Ray Telescope (XRT). Uncertainties quoted are at the 90% confidence level unless otherwise stated. A cosmology where $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_\Lambda = 0.7$, and $\Omega_m = 0.3$ is assumed throughout.

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2. OBSERVATIONS AND DATA REDUCTION

GRB 050904 triggered the *Swift* Burst Alert Telescope (BAT) at 01:51:44 UT. The BAT and XRT data were obtained from the archive and reduced in a standard way using the most recent calibration files. The BAT spectrum is well fit with a single power law with photon index $\Gamma = 1.26 \pm 0.04$ and 15–150 keV fluence $= (5.1 \pm 0.2) \times 10^{-6}$ ergs cm^{-2}, consistent with early results (Cummings et al. 2005; Palmer et al. 2005) that also suggested a duration $T_{90} = 225 \pm 10$ s. An upper limit to the peak energy of the burst, $E_{\rm peak} > 130$ keV, was found by fitting a cutoff power-law model to the spectrum and deriving the 3 σ limit on the cutoff energy. The *Swift* XRT rapidly localized a bright source (Mineo et al. 2005) and began observations in windowed timing (WT) mode at ∼170 s after the trigger, and in photon counting (PC) mode at ∼580 s.

3. RESULTS

The XRT light curve (Fig. 1) fades by >1000 over the first day. But the light curve does not decay as a power law as in many afterglows (Nousek et al. 2005; De Pasquale et al. 2005; Gendre et al. 2006). Instead, the afterglow flares at 446 ± 3 s, doubling the flux. This flaring is similar to that observed in other GRBs at early times (Burrows et al. 2005), but the light curve does not settle into a power-law decay, continuing to be dominated by large variability (up to a factor of 10). The WT light curve is poorly fit by a power law plus a single Gaussian emission peak (χ^2/dof $= 195.7/78$). Allowing a second peak improves the fit (but it is still poor; χ^2/dof $= 125.7/75$), giving central times of 468 ± 3 and 431^{+5}_{-7} s. Dividing the data into hard (2–10 keV) and soft bands (0.5–2.0 keV), it is clear that the later peak is harder and the earlier peak softer (Fig. 2). A two-peak fit to the soft band is acceptable (χ^2/dof $= 41.6/34$)

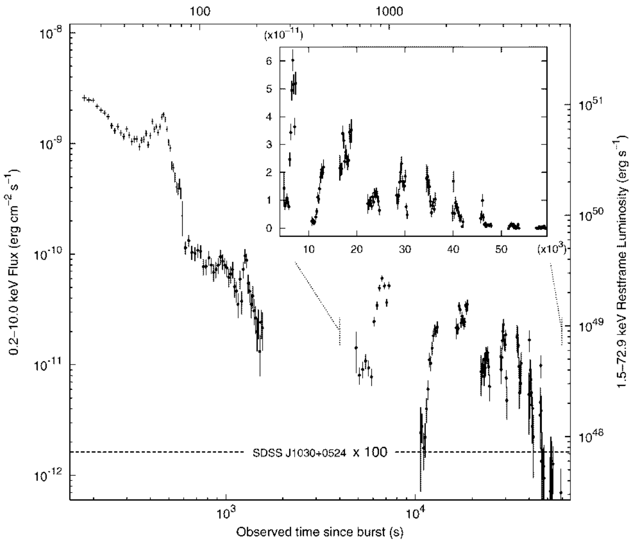

FIG. 1.—*Swift* XRT 0.2–10.0 keV light curve of GRB 050904 (~1.5–72.9 keV in the rest frame). The equivalent isotropic luminosity at $z = 6.29$ is plotted on the right axis. WT and PC mode data are indicated by crosses and dots, respectively. The flux of one of the most luminous X-ray sources known, the AGN SDSS J1030+0524, is plotted for comparison. We have had to multiply its flux by 100 to get it on the plot. SDSS J1030+0524 was the most distant known X-ray source before GRB 050904 and is, conveniently, at nearly the same redshift ($z = 6.28$). *Inset*: Linear blow-up of the data from ~10–70 ks to illustrate the variability of the source at late times. The very hard spectral index at early times ($\Gamma \sim 1.2$) and the long BAT T_{90} for this burst indicate that most of the WT mode data is dominated by prompt emission. However, the continued large-amplitude variability more than 1.5 hr after the GRB trigger (in the rest frame), and the still relatively hard spectrum ($\Gamma \sim 1.9$), suggests that the XRT light curve is dominated by emission from the central engine during the first 12 hr of observations.

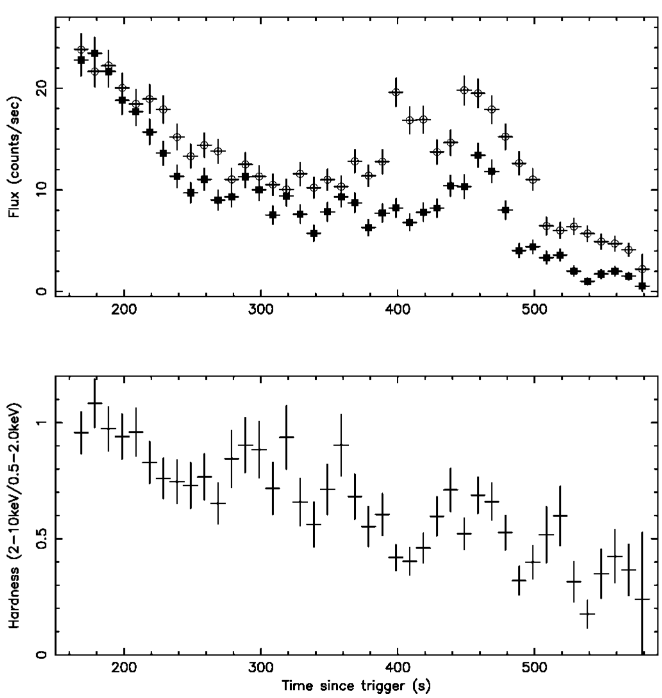

FIG. 2.—*Top*: Soft (0.5–2.0 keV; *open circles*) and hard (2–10 keV; *filled squares*) early light curve of GRB 050904. *Bottom*: Hardness ratio of the early light curve. The hard-to-soft evolution, observed in most GRB prompt emission, is fairly monotonic outside the flares, where small deviations are discernible.

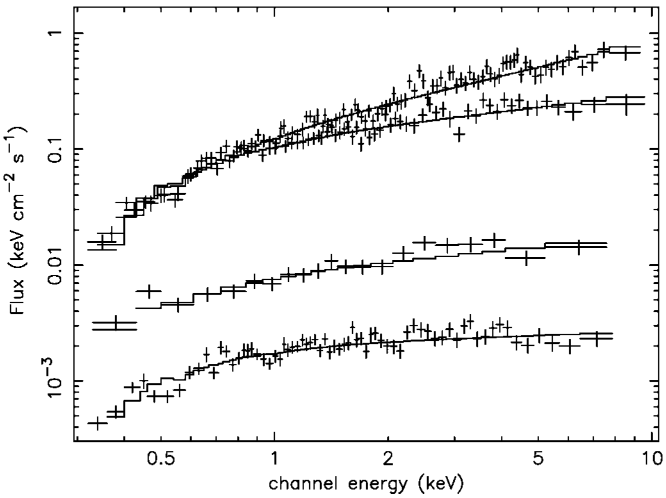

FIG. 3.—*Swift* XRT $E^2F(E)$ (equivalent to νF_ν) spectra of GRB 050904 with the detector response removed. The spectra are fit with absorbed power laws and show a clear hard-to-soft evolution, but the photon power-law indices are consistently $\Gamma < 2$, suggestive of a decreasing peak energy that is above the bandpass ($\gtrsim$70 keV in the rest frame). The best-fit parameters are listed in Table 1.

and gives different peak times than the fit to the full band. There is considerable scatter around this model when fit to the hard-band data, giving an unacceptable χ^2/dof (93.5/34), which suggests greater variability in the hard band on timescales of ~10 s.

The spectra (Fig. 3) can be fit by a hard power law with Galactic absorption (4.9×10^{20} cm^{-2}; Dickey & Lockman 1990). The spectrum softens appreciably during the observation, reaching $\Gamma \sim 1.9$ in the 10–50 ks after the GRB (Table 1). There is no evidence for discrete emission or absorption features. Fe XXVI (6.97 keV) and Ni XXVIII (8.10 keV) at $z = 6.29$ have respective rest-frame equivalent widths <43 and <44 eV in the WT spectra and <27 and <137 eV in the PC spectra. There is some evidence of absorption above the Galactic level: the best fit gives $N_H = (8.3 \pm 0.8) \times 10^{20}$ cm^{-2}. This excess ($N_H = 3.4 \times 10^{20}$ cm^{-2}) is statistically required (significant at a level >5 σ using the F-test). Typical variations in the hydrogen column density at scales $\lesssim 1°$ at high Galactic latitudes are too small to explain this excess (Dickey & Lockman 1990; Elvis et al. 1994). Without discrete features, the redshift of the absorption is essentially unconstrained. Because of the high redshift of the GRB, to observe even a modest column at $z = 0$ requires a high column at $z = 6.29$; in this case the best-fit excess column density at $z = 6.29$ is $(2.8 \pm 0.8) \times 10^{22}$ cm^{-2}. Such a high column could not be considered entirely unexpected; a column density nearly as high as this has been detected before in a GRB (e.g., Watson et al. 2005). Nonetheless, it is intriguing at such an early time in the star formation history of the universe, especially since the absorption is dominated primarily by oxygen and other α-chain elements. However, it should be noted that

TABLE 1
SPECTRAL EVOLUTION OF GRB 050904

Mode	Time since Trigger (s)	Γ	N_H at $z = 6.29$ (10^{22} cm^{-2})
WT	174–374	1.23 ± 0.05	3.3 ± 1.5
	374–594	1.62 ± 0.06	3.6 ± 1.4
PC	594–1569	1.68 ± 0.08	<1.6
	9080–63480	1.88 ± 0.04	2.9 ± 0.8

the combination of the uncertainties in the Galactic column density and the current calibration uncertainty of the XRT response at low energies must render one cautious about the detection of excess absorption in this case.

4. DISCUSSION

The BAT-detected emission overlaps the start of XRT observations and has a power-law photon index close to that observed in WT mode ($\Gamma = 1.3$). It is likely that we are observing part of the prompt emission with the XRT at these times given the similarity with the BAT spectrum, the rapid decay, the flaring, and a spectrum that softens considerably over the first few hundred seconds in the rest frame. This may not be surprising considering that the rest-frame energy band extends to nearly 73 keV. The fact that we are observing higher rest-frame energies in this GRB does not seem to contribute much to the remarkable variability of the light curve, since the soft band (0.5–2.0 keV) has similar overall variability (Fig. 2). The amplitude of these variations seems to indicate continued energy injection from the central engine at least for the first few hundred seconds. Interestingly, the large variability continues as late as 45 ks (Fig. 1), and the spectrum remains hard ($\Gamma < 2.0$), suggesting that significant energy output from the central engine is likely to be continuing at these times, corresponding to ∼6000 s in the rest frame. While continued energy injection at observed times of up to a few hours has been indicated since the launch of *Swift* (Burrows et al. 2005; Nousek et al. 2005), energy injection from the remnant at times of more than half a day was proposed to explain the late-appearing X-ray line emission in GRB 030227 (Watson et al. 2003; Rees & Mészáros 2000). The maximum heights of the later variations in GRB 050904 also seem to decay exponentially, indicating that if accretion onto the remnant is responsible for these variations, the accretion rate is decaying in the same way.

A power spectral density analysis of the light curve shows no significant periodicity independent of the period of the data gaps in the range 10^{-3} to 10^{-4} Hz. The large flaring amplitude and lack of a periodic signal are reminiscent of typical prompt-phase emission from GRBs. However, the total duration of the flaring ($\gtrsim$45 ks) and the individual rise times (a few thousand seconds) are much longer (Quilligan et al. 2002). The overall decay envelope observed here is not typical of prompt emission either, although there are a few cases where such an overall decay is seen (BATSE triggers 678, 2891, 2993, 2994, 7766) and it has been speculated that these continuous decays of the prompt emission result from spin-down of a black hole by magnetic field torques (McBreen et al. 2002).

4.1. *Is GRB 050904 Different?*

Assuming an upper limit to the redshift of GRB formation of $z = 20$ (Bromm & Loeb 2004), the likely maximum age of the GRB progenitor is $\lesssim$650 Myr, consistent with a massive-star progenitor (Galama et al. 1998; Hjorth et al. 2003; Stanek et al. 2003; Woosley & Heger 2006). At this early time in the universe, the question arises whether GRB 050904 could have a different progenitor than GRBs at lower redshift; for instance, a star formed in pristine gas may be one of the massive Population III stars.

Assuming the relation between total energy (E_γ) and $E_{\rm peak}$ (Ghirlanda et al. 2004), the high rest-frame $E_{\rm peak}$ (>940 keV) implies a very high E_γ (>2×10^{51} ergs, consistent with a possible jet break in the near-infrared; Tagliaferri et al. 2005). This high E_γ and the large isotropic equivalent energy suggests that GRB 050904 was intrinsically highly energetic. The persistence of the flaring in the X-ray light curve is also different from typical GRB X-ray afterglows after a few hours (Gendre et al. 2006; De Pasquale et al. 2005). Both the high intrinsic energy output and the large-amplitude, long-duration flaring are notable differences between GRB 050904 and typical GRBs, and might hint at an unusual progenitor. On the other hand, the X-ray flux of the afterglow at 10 hr, $\sim10^{-11}$ ergs cm^{-2} s^{-1}, implies a k-corrected equivalent isotropic luminosity of 5×10^{46} ergs s^{-1}, well within the typical range (Berger et al. 2003). Although if the beaming correction is relatively small, as suggested by the high value of $E_{\rm peak}$, the energy inferred for the X-ray afterglow would also be large.

4.2. *High-z Warm IGM Studies with GRBs*

Access to the edge of the reionization epoch using GRBs has begun with the observation of GRB 050904 at $z = 6.295$. Optical studies of the intervening matter at early times have used quasars (e.g., Becker et al. 2001; Djorgovski et al. 2001; Wyithe et al. 2005), but may be affected by the quasar's significant influence on its surroundings. GRBs are therefore potent tools in this study at optical wavelengths. With X-rays, the warm intergalactic medium (IGM) can be probed. Such work has also just begun to bear fruit with very bright, nearby sources (e.g., Nicastro et al. 2005; see also Fang et al. 2002; Mathur et al. 2003). This is because millions of X-ray photons are required to make these absorption-line measurements reliably (Fang & Canizares 2000; Hellsten et al. 1998). The blazar Mrk 421 ($z = 0.03$) has a bright, intrinsically featureless continuum that provides an easily modeled spectrum against which to detect intervening absorption features. Long exposures (∼250 ks) with the gratings on *Chandra* provided $\sim7.5 \times 10^6$ photons from this source, mostly when the blazar was in extremely bright flaring states. This allowed Nicastro et al. (2005) to detect absorption from ionized C, N, O, and Ne from IGM filaments at $z = 0.011$ and 0.027. The spectra of GRBs in prompt or afterglow emission are usually dominated by a featureless power law (although see Watson et al. 2003; Butler et al. 2003; Piro et al. 2000; Reeves et al. 2002; Mészáros & Rees 2003), as observed in this case, which makes them ideal for studies of intervening matter in a way analogous to blazars (Fiore et al. 2000; Kawahara et al. 2005).

The rapid response of *Swift* to GRB 050904 yielded high signal-to-noise ratio X-ray spectra in spite of the relatively modest aperture of the XRT. This contrasts favorably with observations with *Chandra* and *XMM-Newton* of AGNs at redshifts $z > 5$ that have so far yielded many fewer counts, even in aggregate, in a total exposure time of 300 ks (e.g., Brandt et al. 2001, 2002; Schwartz 2002; Mathur et al. 2002; Vignali et al. 2003; Bechtold et al. 2003; Steffen et al. 2004; Farrah et al. 2004), *excluding* the deep-field observations and in spite of the far larger collecting areas of both instruments.

The >10^{-9} ergs cm^{-2} s^{-1} X-ray continuum detected in the first minutes after GRB 050904 demonstrates the power of GRBs to probe the universe in X-rays to the highest redshifts. Follow-up observations of GRBs with *XMM-Newton* and *Chandra* have shown that in practice the typical fluxes for observations made more than ∼6 hr after the burst (Gendre et al. 2006) are too low to detect the ionized IGM (see Fiore et al. 2000). For instance, GRB 020813, with one of the highest average fluxes, provided about 5000 counts in the *Chandra* gratings over 100 ks (Butler et al. 2003); out of more than 30 observations over the past 5 years, the average observed fluxes are $\lesssim 2 \times 10^{-12}$ ergs cm^{-2} s^{-1}. It is now clear that observations of GRB afterglows with instruments not possessing a very rapid response cannot provide grating spectra with anywhere near 100,000 counts, as had been speculated (Fiore et al. 2000). It is also now clear that a good detection of the IGM requires a flux high enough to provide in excess of 10^6 counts at moderate spectral resolution. It would be feasible to obtain enough photons in 50–100 ks with the Narrow Field Instruments on the proposed *XEUS* mission, if it began observing up to about 6 hr after the burst; with the brighter bursts this might also be possible with *Constellation-X*. But this is clearly not the most efficient way to study the IGM with GRBs. It was suggested as an alternative that a high-resolution instrument with small effective area could make rapid observations of GRB afterglows in their early phases (Fiore et al. 2000). To exploit the huge fluence provided by the high state and flares in the first few minutes after the GRB, a small-area detector could routinely provide 10,000 counts, but this is insufficient for IGM studies (Nicastro et al. 2005). A very rapid response, similar to *Swift*'s, to a GRB like GRB 050904 with a large-area detector with good spectral resolution and fast readout times (e.g., *Constellation-X* or *XEUS*) would reliably yield several to tens of millions of photons in an exposure of only a few minutes. Such short observations would allow studies of the high-redshift universe along many different sight lines, observations that would each require months of *effective* exposure time observing a high-z AGN. Such rapid observations are demanding, but this is a technique now demonstrated in practice by *Swift*, and the short observations would be highly efficient, as well as providing superb spectra. A sample of such observations could allow us to fix the fraction of baryonic dark matter, determine the metallicity and density evolution of the IGM, and put strong constraints on structure formation at high redshifts.

Note added in manuscript.—After submission of this Letter, a paper by Cusumano et al. (2005) appeared, based on an analysis of the XRT and BAT data from GRB 050904. Their findings are similar to those reported here.

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